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# Testing Quantum Erasure and Reversible Quantum Measurement with Holladay's Simple Experiment

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**Abstract.** Schrödinger's continuous differential equation, which, as far as we know, describes the time development of all physical systems, from microscopic to cosmological, is time-reversal invariant. It is the process of measurement of a system that von Neumann found to be irreversible, and may so account for the distinction between past and future. Developed over the last thirty years, quantum eraser theory has claimed that some quantum measurements are reversible. Holladay proposed a very simple double-slit quantum eraser experiment, hitherto never performed, which he said would refute von Neumann's measurement description and support the quantum erasure thesis. Now, that experiment can actually be implemented with inexpensive, easily accessible equipment. Remarkably, results of the experiment refute quantum eraser theory and confirm von Neumann's measurement reduction process instead.

## 1. Introduction

Quantum erasure (QE) has been an influential thesis of the interference phenomena associated with quantum measurement for nearly thirty years. Its advocates say that interference may be eliminated by acquisition (or, in some cases, just availability) of the information indicating which of several alternative paths a *single* system's quantum wavefunction has followed. They assert that erasing that information will restore the interference. [1] Many research groups have now claimed to confirm the quantum eraser phenomenon observationally.

About ten years ago, in response to a criticism of quantum erasure by Mohrhoff [2] some of its proponents have re-construed QE as a more ordinary sorting of the ensemble of measured quantum systems into correlated sub-ensembles. [3] But the preeminent QE experimentalist for many years, Paul Kwiat, has confirmed, with a very recent article, [4] that information erasure resulting in restoration of interference from a simple two-slit screen would indeed be a demonstration of quantum erasure, were one able to insure that just one coherent laser photon were passing through the screen at any time. I'll show here that a very simple incoherent light source and a two-slit screen, much in the spirit of Thomas Young's original experiments, can be used to refute that quantum erasure thesis of interference restoration due to information erasure.

It's well known that the wavefunction evolution of all non-relativistic physical systems, of whatever size, can be described by Schrödinger's differential equation. Such wavefunction development is time-reversal invariant and incapable of the distinction between past and future that is indicated, for instance, by the monotonic increase in entropy (and decrease in information) mandated by Planck's formulation of the second law of thermodynamics. [5] Von Neumann, however, disputed Schrödinger's well-known, avid contention [6] that all of wavefunction development is continuous and reversible. Seconded by Bohr and Heisenburg, among many others, even today, he argued that there is a disparate, discontinuous event which transforms the wavefunction at measurement. [7] And he found this distinct development, named "process 1", to be irreversible.

In contrast, during the last thirty years, the seminal, theoretical development of quantum erasure has become the most persistent and influential defense of continuous Schrödinger evolution during quantum measurement. Marlan Scully and his collaborators claimed to show that the wavefunction of a spinning particle in a Stern-Gerlach magnet can evolve continuously, even as which path it takes through the magnet is measured. [8] In fact, employing continuous wavefunction evolution, they calculated a nearly diagonalized density matrix beyond the magnet for this historic prototype of quantum measurement.

But in spite of many experiments now claiming to confirm the quantum eraser hypothesis, that theory, and continuous wavefunction development during measurement, has not been established scientifically. It's obvious, in fact, from the myriad of contradictory theses, that even today, eighty years after its advent, there exists no consistent, comprehensive theory of measurement in quantum mechanics.Ballentime has said that "It is now widely understood that von Neumann's 'reduction' is not a real physical process (which would contradict the equations of motion for the combined system plus apparatus, and so make the theory hopelessly inconsistent)." [9] While Holladay, on the other hand, has labeled von Neumann's reduction process the "orthodox" view. [10] Indeed, I believe it is the lack of an understanding of the *process* of quantum measurement which is the ascendant source of the current confusion and controversy in quantum theory.

Below, in section 2, I show that Scully's theoretical analyses of Stern and Gerlach's experiment, upon which all of quantum erasure is based, is clearly not credible. Holladay suggested a very simple, optical, double-sit experiment which he said would confirm quantum erasure and refute von Neumann's quantum measurement reduction. [11] I devote section 3 to its description and implementation. I've explained how to use a small, incoherent (random phase) light to actually perform the experiment. Remarkably, that experiment refutes quantum erasure and supports von Neumann's explanation. Section 4 includes related comments and conclusions. A forthcoming article examines other, more sophisticated, optical experiments also purporting to confirm quantum erasure. Careful, critical analysis of those experiments shows them to also, simultaneously, confirm hypotheses incompatible with quantum erasure.

## 2. Theoretical Test

Quantum eraser theory began with the mathematical analysis of a modified Stern-Gerlach experiment developed by Marlan Scully, R. Shea, and J. D. McCullen (SSM) in 1978. [12] The authors installed a bi-level atom along one of the two possible paths of a heavy, spin one-half molecule traversing an inhomogeneous magnetic field. The molecule is said to invariably kick the atom from its ground to its excited state if it travels the route occupied by that atomic detector. This would, according to our usual Stern-Gerlach analyses, measure the spin direction of the molecule from its deflection by the magnetic field. Crucially, SSM supposed that a detector atom much lighter than the spinning molecule would transfer negligible momentum to the molecule at collision, and so result in no effective change of the molecule's quantum wavefunction. Employing this assumption, they derived a nearly diagonalized density matrix for the atom-molecule system after detection. Since SSM assumed that time-reversible, continuous Schrödinger evolution describes the entire passage of the molecule through the magnetic field, this would seem to satisfy Schrödinger's ardent conviction that there exist no quantum jumps, even at measurement. According to SSM, "This 'state reduction' (i.e. the loss of off-diagonality of the density matrix of the system) takes place even if the system is not 'messed up' or perturbed in the process of 'looking'." [13]

Note, however, that SSM ignored the quantized energy, always equal to the difference between the atom's ground and excited level, transferred from the molecule to the atom at collision. And, that every unique energy eigenvalue of the molecule is associated with a different, linearly-independent eigenfunction, which specifies a different measured molecular state. So, one is justified in denying the continuous development of the molecular wavefunction at detection, essential to the SSM analysis.

Nevertheless, Scully suggested that the SSM analysis might describe a real physical phenomenon called quantum erasure. He and his colleagues had written that if "we reverse time and pass our spins back through the apparatus, allowing them to again interact with the detector, the interaction could take an excited detector atom back to the ground state and return the total system to a pure case…." [14] This could imply that if the wavefunction of the measured object evolved continuously when information was provided to the detector (bi-level atom), then erasing that information should reverse the effects of measurement on the object. And, Scully and Walter reiterated this understanding some twenty years later "…if we put a *WelcherWeg* detector in place (so we lose interference even if we don't look at the detector) and then erase the which way information after the particles have passed through…such a 'quantum eraser' process (would) restore the interference fringes." [15] And, there appears to be no useful way to interpret this, the original, foundational description of quantum erasure, as an effective method for re-sorting an ensemble of incident particles.

Early on, Scully and his collaborators proposed several devices that might be used to confirm the reality of quantum erasure, but they initially proved impractical. [16] More recently, many groups claim to have confirmed quantum erasure experimentally. But, such confirmation may not be completely convincing. We shall see that hypotheses other than quantum erasure can often explain those results. Attempted refutation of a scientific hypothesis, rather than repeated confirmation, is the appropriate test.

## 3. The Holladay experiment

Holladay proposed a double-slit screen illuminated by a monochromatic light source (presumably, a "point" source,) as a quantum erasure devise, Figure 1. [17] He explained that a Young-type interference pattern would be produced on a far-field screen by each incoherent photon's wavefunction that passed through both slits. Then each slit is covered with a Polaroid filter, one horizontal, and the other vertical. Holladay wrote that the crossed Polaroids "label" each possible path which a photon may travel. And, of course, observation shows that those crossed Polaroids do eliminate the interference pattern.

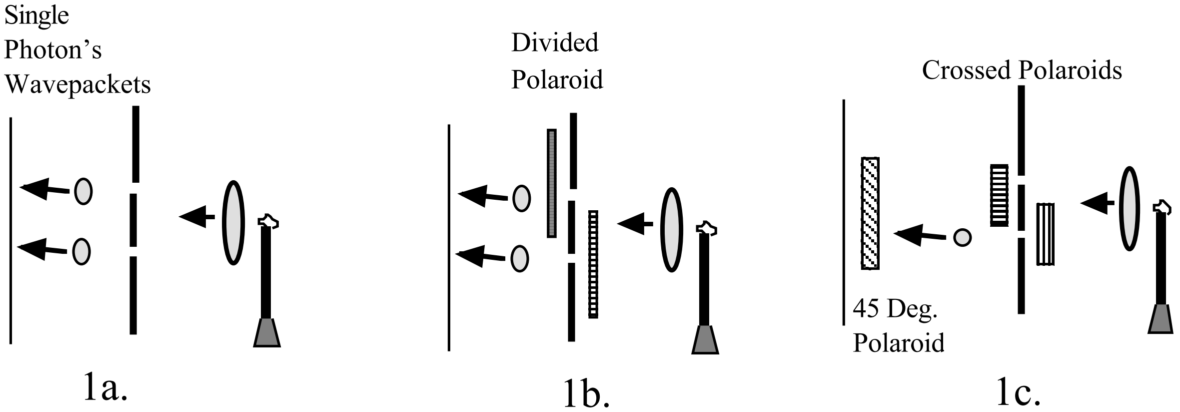

Figure 1. A minimaglight flashlight filament acts as a point source of incoherent, white light. When positioned about a meter from a two-slit screen it can produce a Young's interference pattern on a viewing screen. Polaroid filters project the wavefunction on to just one of many polarization eigenfunctions.

To confirm quantum erasure, Holladay would cover both slits and their crossed polarizers with another Polaroid filter, this one at forty-five degrees from horizontal or vertical, Figure 1c. The Young's interference pattern, albeit at a reduced intensity of 25 percent, is supposed to reappear. According to the standard quantum erasure hypothesis, the final Polaroid is said to erase the which-way polarization information carried by a probability amplitude along each path. That last Polaroid is at forty-five degrees to each orthogonal polarizer, and the probability that a photon at the viewing screen traveled either path is one half. So, it's not possible to specify which way a photon went. Such an information erasure in the two amplitudes is believed by quantum eraser proponents to account for the putative, restored interference. Significantly, that interference revival was not tested by observation.

If we suppose, as Holladay did, that the final polarizer would restore interference, then "when the path of the photon is labeled by a definite state of polarization…, so that the photon with that particular polarization transits definitely one (or the other) of the paths, it does not make sense to say that the wave 'collapses' along that path and that the amplitude along the other path vanishes. If this phenomenon occurred, it is very difficult to see how the insertion of the quantum eraser Polaroid could restore the interference of amplitudes *from both paths.* Thus, these experiments call into serious question the orthodox position of von Neumann and his followers that posit a dual dynamics in quantum mechanics – the normal unitary change in the wave function given by the Schrödinger time dependent equation *and* the non-unitary change given by von Neumann's projection postulate….In these quantum eraser experiments apparently the photon is definitely traversing one path (or the other) but the wave, with one path 'empty', continues along both paths as manifested by the restoration of interference by the quantum eraser." [18] But, Holladay only presumed that interference would return. Until very recently, the actual observation had not been attempted.

Within the last few years, Paul Kwiat, the most prominent of the QE experimentalists, and his student, Rachel Hillmer, described a do-it-yourself quantum eraser demonstration. [19] It's almost identical to Holladay's proposal, so confirming the suitability of that simple experiment as a real test of the QE theory. They replace the double slits with a thin, straight wire to generate an interference pattern, and employ a small laser, like a laser pointer, rather than an incoherent light source. Then, Polaroid filters in the usual orientations are arranged as a demonstration of the quantum eraser phenomenon. They show how two orthogonal polarizers, one on either side of the wire, will provide the information to distinguish which way a photon traveled, destroying interference. Then, an additional forty-five degree Polaroid, covering the crossed polarizers, acts as an "eraser…, something that can erase the information indicating which path each particle has followed, thereby restoring the indistinguishability of the alternatives and restoring interference." [20] This last Polaroid does revive interference.

But, the authors recognize that only if one photon at a time passes the thin wire and polarizers can one claim genuine observational confirmation of quantum erasure. Otherwise, because the laser creates innumerable, coherent photons, the interference pattern, originally produced and then revived, could result from two particle-like photons passing simultaneously to either side of the wire. (Dirac's admonition that a photon only interferes with itself [21] was incorrect. Unfortunately, in spite of Glauber's efforts, [22] many physicists remain in the dark about this.) . Quantum erasure is supposed to revive interference due to a *single* system's wavefunction that still travels both ways, even after the which-way path has been detected. Kwiat emphasizes this point: "…you could only truly prove that…individual photons that make up the light wave are indeed doing the full quantum dance…by sending the photons through the apparatus and detecting them one at a time." [23] Or, by using incoherent photons so that only those individual photon wavefunctions that transit both slits contribute to interference.

## 4. Performing the experiment

Wonnell demonstrated the use of a tiny, Minimaglight, incandescent, flashlight filament, 1.3mm long and 0.25mm wide, to produce a two-slit, Young's interference pattern. [24] Such an incandescent light source is very unusual today when inexpensive, versatile lasers are conveniently available. Moreover, the chaotic source generates white-light photons that are bunched together [25] and have an extremely short coherence length. Nevertheless, unlike a laser, it does possess the essential property that interference can be constructed from only those photons' wavefunctions that pass through both of the two slits. What it lacks in modern sophistication it supplies in efficient functionality, and can actually be used to test quantum erasure. With the filament exposed by removing the lens cover and set up about one meter from an appropriate two-slit film, like a Cornell Slitfilm Demonstrator, that filament acts as a point source of incoherent, white light. With a two-slit film of about 0.1 mm width, and about 0.3 mm separation I implemented Holladay's experiment.

I recorded the photograph of Figure 2a with one slit covered by opaque material. A small (4 megapixel) digital camera, focused on infinity, was secured a few centimeters from the slit film, and automatically adjusted the timed exposure to a few seconds. The resulting Fraunhofer diffraction pattern takes the form, $\frac{I(\theta)}{I_0} = \frac{\sin^2\beta}{\beta^2}$, with $\beta = \frac{\pi a \sin\theta}{\lambda}$, where I is the light intensity, $I_0$ is intensity at the center of the pattern (q = 0), l is the wavelength, and $a \approx 0.1$ mm, in this instance, is the slit width. The same arrangement, now with both slits open, was used to take the photograph of Figure 2b. Young's interference, characterized by equally spaced maxima, is plainly seen superimposed on the Fraunhofer image. The pattern is a product of Fraunhofer diffraction and Young's interference, $\frac{I(\theta)}{I_0} = \frac{\sin^2\beta}{\beta^2}\cos^2\gamma$, with $\gamma = \frac{\pi d \sin\theta}{\lambda}$, where $d \approx 0.3$ mm was the slit separation. There is, of course, some color aberration, due to the white light, but not so much that the patterns are obscured.

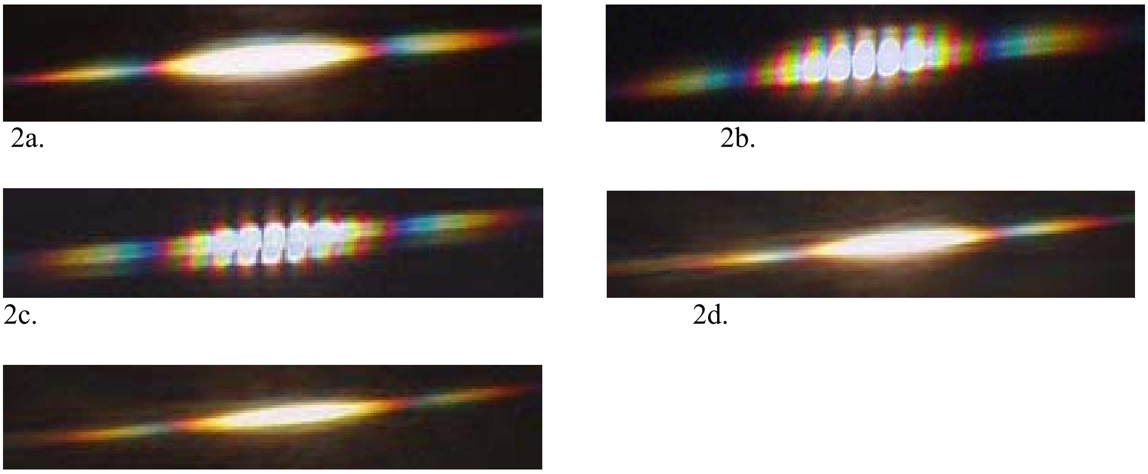
2a. 2b.
2c. 2d.
2e.

**Figure 2.** The first photograph, 2a, shows the Fraunhofer pattern produced by a single slit. Figure 2b is the Young's interference pattern resulting from two slits, each identical to the single slit of the first photograph. The next photograph, 2c, shows that two separate polarizing filters, one over each slit, if aligned, still result in interference at the viewing screen. Figure 2d is the photograph when the slits are covered by crossed Polaroids. Figure 2e is the resulting photograph, indicating no restored interference, if a forty-five degree Polaroid covers the crossed polarizers. Color, and much improved resolution, may be available on-line.

Wonnell has measured the very short coherence length of photons from the Minimaglight filament at about ten microns. [26] Following Holladay's prescription for a quantum eraser experiment, it's necessary to cover each slit with a piece of polarizing film. Unless those two, crossed Polaroids have nearly identical film thickness, tiny differences in optical path length, rather than orthogonal polarization through each slit, could prevent photon overlap, eliminating interference. So, I placed one piece of polarizing film over each slit, with each polarization axis aligned horizontally. The photograph, Fig 2c shows that Young's interference persists. And, the two pieces of Polaroid (cut from the same sheet of film ) must be of very nearly identical thickness, since wavetrains from the flashlight continue to overlap at the viewing screen.

Next, I oriented these two polarizing films ninety degrees from each other. The photograph, Figure 2d, shows that Young's interference is eliminated by the orthogonal polarizers. But not eliminated by a difference in optical path length through the two films, since they have essentially uniform thickness. Finally, as prescribed by quantum eraser theory, I placed a Polaroid film with axis forty-five degrees from vertical over the two slits and crossed Polaroids, Figure 1c. The photograph, Figure 2e, shows clearly that the Young's interference pattern is not restored as quantum erasure requires. Moreover, the use of a collimated sodium arc lamp, for instance, with the same arrangement, would, no doubt, reinforce this conclusion with nearly monochromatic photons of substantially longer coherence length.

Though it's often forgotten or ignored, even some prominent supporters of the QE theory recognize that a Polaroid filter acts as a von Neumann-type projection operator in the mathematical formalism of quantum mechanics. [27] The wavevector of an incident photon approaching the double-slit film with crossed polarizers is in a superposition, $\left|\boldsymbol{\Psi}(\mathbf{r},t)\right\rangle = \frac{1}{\sqrt{2}}\left(\left|\psi_1(\mathbf{r}_1,t)\right\rangle\left|\chi_{\phi+90}\right\rangle + \left|\psi_2(\mathbf{r}_2,t)\right\rangle\left|\chi_\phi\right\rangle\right)$, where either of two possible polarization directions, $\phi$ or $\phi + 90$ degrees, are possible when measured. Schrödinger time development of the wavefunction is unitary and continuous and it cannot evolve a superposition of polarizations into just one value. But, as von Neumann explained, the Polaroids *project* just one of these two eigenfunctions, and they erase phase information in the wavefunction. That is a *measurement* of each photon's polarization, so the photon wavefunction can survive on only one path from the two slits. Therefore there can be no possibility of resurrecting interference after the polarization measurement, as predicted by quantum erasure.

Incandescent photons are more likely to be bunched together than those from a laser, so a minimaglight filament might generate more coincident, overlapping photons at the two-slit screen than a laser. If two such incoherent photons reach the crossed Polaroids and slit film at the same time, the probability is one-half that each will traverse a different slit, even after projection to just one path by a polarization measurement. But, crucially, the forty-five degree polarizer cannot restore the interference, it cannot reverse measurement, because those two photons have random phases. Two coincident, coherent laser photons (as in the Kwiat-Hilmer demonstration) only seem to reverse the polarization measurement because they are in phase, and so they can restore interference even after transiting different slits. It is essential that a real QE experiment demonstrate measurement reversal (as in interference restoration) in single quantum systems.

An experiment that claims to have done this was recently reported by Schneider and La Puma. [28] Their experiment is very similar to Holiday's proposal. Instead of a double-slit screen, they used a Mach-Zehnder interferometer, which also can divide a single photon's wavefunction along two indistinguishable paths. A well-defined interference pattern of many light and dark fringes is recorded in a simple digital camera if a small laser provides photons to their interferometer. They place crossed Polaroid filters in each arm of the interferometer and this is supposed to encode the photon's path in its polarization. As they show, it does wipe out the interference pattern. Then, they place a third Polaroid, oriented at forty-five degrees, over the output of the interferometer. This is said to erase the which-way encoding. It is clearly shown to revive the photographic image of many light and dark fringes in the interference pattern.

Schneider and LaPuma are aware, of course, that even a small laser (they don't tell us its power or wavelength) produces a prodigious number of photons per second. And, an hypothesis of two simultaneous coherent photons traveling separate interferometer paths, with overlying wavetrains at the camera, would also account for their observed result, instead of confirming the quantum erasure of a single system. So, they attenuate their laser by a factor of about $10^9$, which is supposed to eliminate the possibility of overlapping photons. This produces a resurrected, wavering, and very tenuous, single dark fringe over a light background in the observed pattern. [29]

Without specifying the coherence length of photons from their laser, the authors say that the distance between photons, on average, is about ten times their coherence length. This means that there is about a ten percent chance that one photon (emitted at random) in the attenuated beam will overlie at least half the wavetrain of another. This may be sufficient to account for the single, revived dark fringe, when each of those two photons passes simultaneously along a different arm of the interferometer. Even in an undergraduate laboratory, one could easily check the source of that single dark fringe by comparing attenuation of the laser beam with a corresponding lengthening of exposure time at the camera. Attenuation would reduce overlap, and beam intensity too, of course, but lengthened exposure time would only increase the resolution at the interference pattern.

## 5. Conclusion

Erwin Schrödinger was adamant that all time evolution of the quantum wavefunction is continuous, even during measurement. For over thirty years the most influential support for Schrödinger's view has been supplied by quantum eraser theory. That theory is founded on an analysis of Stern and Gerlach's experiment by Marlan Scully and his collaborators from 1978. But a critical evaluation of the Scully, Stern-Gerlach analysis shows that it is not credible. Though many experiments now claim to confirm quantum erasure, it's easy to refute that hypothesis with an incoherent light source in Holladay's experimental arrangement. Even a very simple flashlight filament, double-slit film, and several Polaroids are adequate to test the QE proposition. Unlike many other QE experiments, which claim to confirm that theory, the incoherent light source, rather than a laser, can be essential for actually testing quantum erasure.

We also need to recognize that observations which corroborate predictions of one theory may simultaneously support other, contradictory hypotheses. And that the more reliable test of a proposed scientific theory, like quantum erasure, is attempted refutation, not confirmation. Still, I've briefly addressed some other QE experiments in a forthcoming article. [30] Careful analyses show that those experiments, too, also support hypotheses incompatible with quantum erasure.

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